AL/HR-TR-1994-0168

ARMSTRONG LABORATORY

ALTITUDE CUING EFFECTIVENESS OF TERRAIN TEXTURE CHARACTERISTICS IN SIMULATED LOW-ALTITUDE FLIGHT

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March 1995

Final Technical Report for Period May 1989 - January 1993

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This report has been reviewed and is approved for publication.

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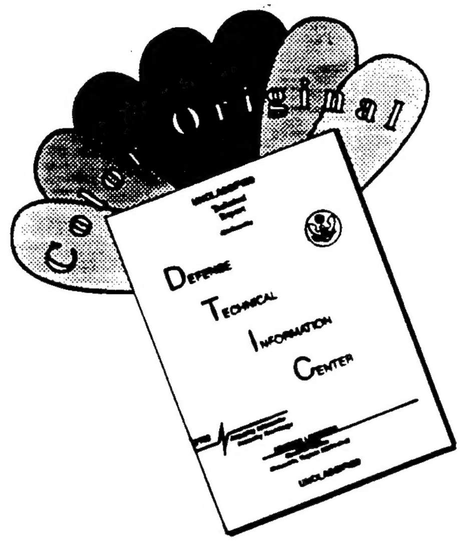

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
March 1995

3. REPORT TYPE AND DATES COVERED
Final May 1989 - January 1993

4. TITLE AND SUBTITLE

Altitude Cuing Effectiveness of Terrain Texture Characteristics in Simulated Low-Altitude Flight

5. FUNDING NUMBERS

C- F33615-90-C-0005
PE - 62205F
PR - 1123
TA - 03, 32
WU - 85, 03

6. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Armstrong Laboratory (AFMC)
Human Resources Directorate
Aircrew Training Research Division
6002 S. Power Road, Bldg 558
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10. SPONSORING/MONITORING AGENCY REPORT NUMBER

AL/HR-TR-1994-0168

11. SUPPLEMENTARY NOTES

Armstrong Laboratory Technical Monitor: Dr Elizabeth L. Martin, (602) 988-6561

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Two experiments were conducted to determine the altitude cuing effectiveness of various terrain texture characteristics in simulated low-altitude flight. In Experiment 1, we compared the effects of five different texture conditions, two types of subjects (pilots versus nonpilots), and direction of altitude change (ascent versus descent) on altitude change discriminability. Results indicated that performance varied significantly as a function of texture, pilots were more sensitive than nonpilots to changes in altitude, and simulated descents were easier to discriminate than ascents. Experiment 2 involved an investigation of the effects of four of the five texture conditions previously used, direction of altitude change, and two levels of texture contrast that simulated normal daytime and dawn/dusk lighting on the detection of change in altitude. We again observed that descents were more discriminable than ascents, but unlike the first experiment, performance did not vary as a function of texture. Further, simulated dawn/dusk terrain lighting did not adversely affect performance.

14. SUBJECT TERMS
Altitude cuing , characteristics, cuing effectiveness, flight simulation, flight training, low-altitude flight, simulators, terrain, texture

15. NUMBER OF PAGES
48

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION ABSTRACT
Unclassified	Unclassified	Unclassified	UL

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PREFACE

The research program described in this report was conducted at the Aircrew Training Research Division of the Armstrong Laboratory to investigate the terrain texture requirements for low-altitude flight simulation. This research effort was supported by the University of dayton Research Institute, Contract No. F33615-90-C-0005, in conjunction with Work Unit Nos. 1123-03-85, Flying Training Research Support, and 1123-32-03, Tactical Scene Content Requirements. The contract monitor was Ms. Patricia A. Spears. The work unit was Dr. Elizabeth L. Martin.

The authors wish to acknowledge the outstanding support provided by the following individuals:

Mr. Carlos Zavaleta and Ms. Debra Murray, who developed the data collection and reduction software, and

Mr. Jovan Raketich, who modeled the terrain texture conditions.

ALTITUDE CUING EFFECTIVENESS OF TERRAIN TEXTURE CHARACTERISTICS IN SIMULATED LOW-ALTITUDE FLIGHT

INTRODUCTION

A number of flight simulator visual systems that use computer-generated imagery (CGI) to simulate the external aircraft scenes include a capability to apply texture in the scenes. This texture consists of two-dimensional patterns of fine detail that are superimposed upon the features comprising the scenes. An important advantage of texture is that it can be rendered on the terrain surfaces to provide cues for the control of aircraft altitude in the simulation of low-altitude flight. These cues are produced as the simulated aircraft undergoes a change in altitude close to the terrain. In the case of descending flight, the cues can include an apparent increase in the size (magnification) of the terrain details, an apparent spreading apart (divergence) of the details, and an apparent increase in velocity (acceleration) of the details streaming under the aircraft.

Recent enhancements in texturing technology now make it possible to use almost any texture pattern in the visual scenes. Thus the question arises within the flight simulation community concerning the specific details that should be included in terrain textures to maximize their altitude cuing effectiveness. This question served as the impetus for the present research in which the cuing efficacy of various terrain texture conditions in simulated low-altitude, high-speed flight was compared. Before describing the specifics of the research, an historical overview of the more significant texturing techniques that have been implemented is presented and the terrain textures that have been subjected to previous simulator experimentation are identified.

Terrain Texturing Technology

CGI systems have traditionally used polygons (previously called faces) to represent the features contained within the visual scenes, including the terrain surfaces. Polygons were also used in early CGI systems to create texture effects on the scene features (Monroe, 1975). A checkerboard terrain pattern, for example, was produced by modeling a set of square polygons for the terrain surface and then reducing the luminance of every other square. An alternative texturing technique used in early CGI systems, which was referred to as smooth shading, linearly varied the luminance across the individual polygons within a texture pattern (Bunker, Economy, & Harvey, 1984; Phelps, 1984). With smooth shading, the polygons appeared curved, or rounded, and the sharp and distinct edges between the individual polygons were eliminated.

Terrain texture produced from polygons, however, was deficient in several important respects. First, even with smooth shading, the polygon structure did not appear very realistic. Second, the number of polygons required in a texture pattern imposed a severe burden upon the image generators because of their limited polygon processing capabilities. This forced the use of relatively large polygons on the terrain and restricted the use of smaller polygons to only critical areas within the scene. Third, the area on the terrain bounded by each polygon was still devoid of detail, which meant that as the observer moved closer to the terrain surface, less detail was visible.

These deficiencies were subsequently alleviated through the application of texturing techniques that provided fine detail within the polygons. Of the various techniques that were developed, several used a mathematical function or a combination of functions to produce the texture. One of these texturing techniques implemented a mathematical function that was driven

with white noise (Bethke, 1980). Another used a function that was the product of the sums of sine waves (Gardner & Gershowitz, 1982). A further technique was developed using cyclic pseudorandom noise coding algorithms (deSpautz, Bender, & McNamara, 1980). In addition, General Electric introduced a mathematical technique that provided parallel stripes with varying orientations, which was known as stripe texturing (Bunker et al., 1984).

Most of the remaining texturing techniques that were developed to provide fine detail within the polygons display a combination of photographic and synthetic textures. Such techniques are used in the more advanced CGI systems that are currently available (Nash, 1991). Photographic textures are created from digitized aerial or satellite photographs of natural scenes (or any other subject matter) and the synthetic texture patterns are created from several different methods, including hand digitizing, mathematical procedures, and fractal methods that attempt to imitate nature. These textures are stored in computer memory as two-dimensional data arrays called texture maps. The maps are applied to the polygons and modulate the polygon's luminance or color. Large surface areas are usually textured with self-repeating patterns and filtering removes the discontinuities between the individual patterns. In some cases, more than one map is applied to a single polygon, each with a different scale factor so that as the simulated viewing distance increases, the texture with the smaller scale factor is attenuated and the texture with the larger factor remains. Additionally, the maps may be translated in the plane of the polygon to simulate texture motion. For detailed examples of these techniques, refer to Economy, Ellis, and Ferguson (1988), Jarvis (1990), Robinson and Zimmerman (1985), and Yang, Wood, and Wallner (1986).

Previous Terrain Texture Research

A variety of studies have been conducted to examine the effects of terrain texture characteristics on performance in simulated low-altitude flight. The results of these studies, however, have limited applicability in determining the textures to use in modern CGI systems for low-altitude flight simulation. The reason for this is that the terrain textures that were subjected to experimentation were rather sparse and lacked the level of detail and complexity achievable in today's flight simulators. In the studies, the following terrain texture conditions were compared:

(1) checkerboard patterns with different square sizes (Buckland, 1980);

(2) a uniform green surface and a simulated farmland with different shapes and shades of color (Rosenberg & Barfield, 1991);

(3) a pattern with lines perpendicular to the flight path, a pattern with lines parallel to the flight path, and a grid pattern containing both line orientations (e.g., Flach, Hagen, & Larish, 1992; Johnson, Tsang, Bennett, & Phatak, 1989; Wolpert, 1988);

(4) a random field of dots, a simulated roadway with two parallel lines converging at the horizon, and a combination of the dots and the roadway (Warren, 1988); and

(5) colored rectangles of varying size (e.g., Hettinger, Owen, & Warren, 1985; Tobias & Owen, 1984; Zaff & Owen, 1987).

Scope of the Present Research

The present research encompassed two flight simulator experiments in which we examined the effects of various advanced terrain textures on the detection of altitude change in low-altitude, high-speed flight. Five different texture conditions

were compared in the first experiment and four of the five were used in the second experiment to assess the repeatability of the texture effects. A psychophysical procedure was used to measure altitude change discriminability. Subjects were presented a series of paired simulator trials depicting a standard and a comparison altitude. The standard altitude was always 100-ft above ground level (AGL) and the comparison altitude was varied. The subjects' task was to indicate whether the two altitudes portrayed in each trial pair were the same or different. An airspeed of 500 kt was used to simulate high-speed flight. Subjects participated as observers only, they did not have control of the simulated aircraft.

Due to inconsistent results in previous research, it has been suggested (Flach et al., 1992) that the effects of terrain texture on performance are contingent upon the characteristics of other factors in the simulation such as the type of subjects and performance task. To assess the degree to which such factors may influence the effects of the advanced textures presented in the current research, we also varied the direction of altitude change relative to the standard altitude in trial pairs, subject flight experience, and terrain lighting. In each of the two experiments that we conducted, a different combination of these factors was used.

EXPERIMENT 1

In the first experiment, we examined the effects of the five terrain texture conditions on altitude change detection performance in relation to direction of altitude change and subject flight experience. We varied the direction of altitude change through the use of comparison altitudes in the trial pairs that were above the standard 100-ft altitude and below the standard, which represented ascending and descending altitude

changes, respectively. The effects of subject flight experience were measured using a group of pilots and group of nonpilot subjects. An assessment of the relationship between the direction of change in aircraft altitude and the cuing effectiveness of the terrain textures was included in the experiment because the efficient detection of both a descent and an ascent is crucial in low-altitude, high-speed flight. A pilot must be able to efficiently perceive a descent in order to avoid the possibility of colliding with the terrain and similarly an ascent to prevent an inadvertent increase in altitude that could expose the aircraft to enemy radar detection. Subject flight experience was compared to determine if experience in the actual aircraft facilitates ascent and descent discriminability and if the relative altitude cuing efficacy of textures varies as a function of type of subject.

Method

Subjects

A total of 20 male subjects participated, 10 active duty U.S. Air Force T-37 and T-38 instructor pilots and 10 nonpilot military and civilian subjects with normal or corrected-to-normal visual acuity. The mean, minimum, and maximum accumulated military flight time of the pilots were approximately 1,540, 330, and 3,850 hr, respectively. Contrast sensitivity was measured for each subject using the Vistech Consultants, Inc., Vision Contrast Test System (VCTS), Model 6500. Test stimuli were monochromatic gratings that varied in contrast. The spatial frequencies of the gratings were 1.5, 3, 6, 12, and 18 cycles per deg. Test results indicated that the subjects had normal contrast sensitivity functions.

Apparatus

The visual scenes were generated using the General Electric Advanced Visual Technology System (AVTS), which provides photographic texturing [see Eibeck & Petrie (1988) for specifications]. The scenes were displayed on the interior surface of a semicircular dome. Display field of view was 110-deg horizontal by 85-deg vertical. A General Electric color light-valve projector was used to display the imagery. The addressable resolution of the light valve was 985 lines by 1,000 elements per line.

The subjects were seated facing the display surface, and the viewing distance was five ft. The light-valve projector was located above and behind the subject. Black curtains were placed around the open half of the dome to block out extraneous light.

A hand-held box was provided containing two pushbutton switches, which the subjects used to enter their responses. One switch was labeled SAME, the other labeled DIFFERENT.

A researcher/operator console was located adjacent to the dome. The console contained two cathode ray tube (CRT) monitors and a typewriter keyboard. One of the monitors displayed the same visual imagery that was presented in the dome; the other monitor displayed the subject's responses, the current simulated altitude, and a variety of other trial information. The keyboard was used to enter the study conditions and to start the experimental trials.

Terrain Textures

The textures were created in the scenes by modulating the luminance of the polygons comprising the terrain surface. The

underlying color of the polygons was tan and the sky was blue. The terrain surface was flat and there were no objects in either the sky or on the terrain surface.

Instead of using photographs of actual terrain surfaces for the texture conditions, we designed the five different textures that were compared in this experiment. We chose to design the textures for two reasons. First, we felt that photographs of actual terrain might limit the applicability of the results to those specific terrain conditions. Second, this approach allowed us to precisely control the characteristics of the textures.

One of the textures we used (Terrain Texture 1) portrayed irregularly shaped patches that were randomly positioned on the terrain surface. This texture was created from a digitized photograph of shredded cotton balls, and the photographic image was repeated over the surface of the terrain. An overhead view of the texture at a simulated altitude of 1,000 ft is presented in Figure 1. The subject's view of the texture in the experimental trials is shown in Figure 2 at an altitude of 100 ft. For the overhead and subject's views, the aircraft was respectively pitched downward 45 deg and 20 deg from level to display more of the texture on the CRT monitor from which the photographs were taken. The reasons for the use of a texture condition consisting of random patches were that it provides considerable detail on the terrain surface and this type of terrain texture is currently presented in most simulations that allow texturing.

Three of the other four texture patterns (Terrain Textures 2 through 4) depicted parallel bands of fine texture detail on the terrain surface. In each pattern, three band orientations were used: 40 deg, 75 deg, and 155 deg from zero-deg north. The texturing within the bands was created by applying a mathematically produced noise pattern on the terrain surface and

Figure 1. Terrain Texture 1 (overhead view).

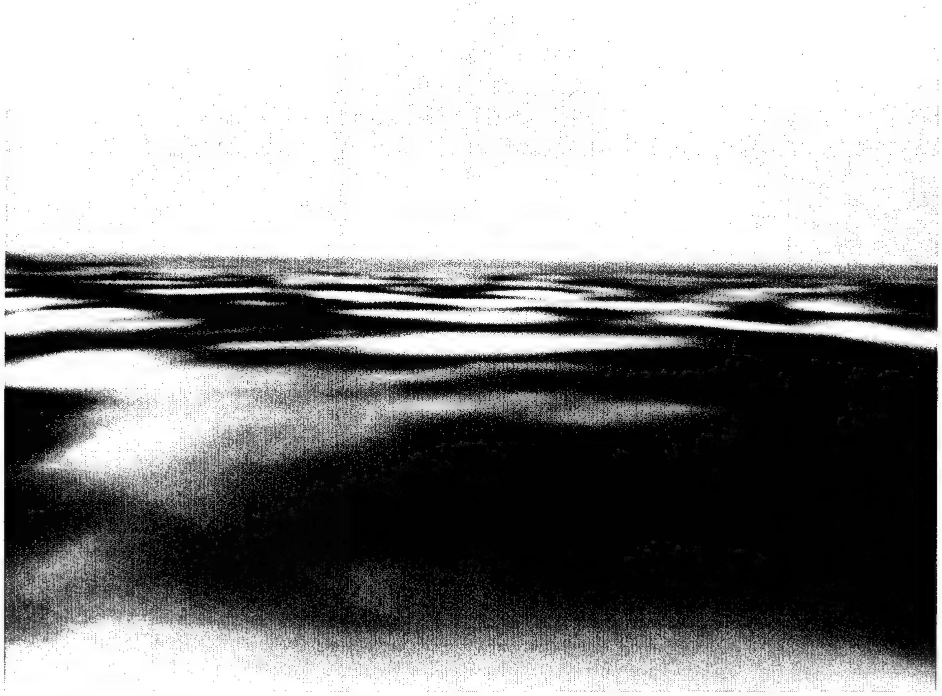

Figure 2. Terrain Texture 1 (subject's view).

then removing the pattern between the bands. The band structure was implemented to simulate differences in the type and density of detail across the terrain surface and to provide distinct borders between one area of detail and the next, both of which are commonly encountered in the real-world flight environment.

Terrain Texture 2 is shown in Figures 3 and 4 from an overhead perspective and from the subject's viewpoint, respectively. All bands were 100-ft wide. A 30-ft-wide textured strip was added along the centerline to increase the detail within the bands. The separation between the bands was constant within a given band orientation. However, a different band spacing was used for each of the three orientations in order to vary the sizes and shapes of the nontextured areas on the terrain, as is typical in real-world settings. For the 40-deg band orientation, the spacing was 500 ft; for the 75-deg orientation, it was 1,000 ft; and for the 155-deg orientation, it was 2,000 ft.

Figures 5 and 6 show the overhead and subject's views of Terrain Texture 3. For this texture, the widths of the bands were increased to 300 ft and the center strip in the bands to 100 ft. The wider bands were used to increase the amount of detail within the bands. The spacing between the bands was the same as in Terrain Texture 2.

For Terrain Texture 4, the spacing between the bands within each of the three orientations was varied so as to eliminate the temporal regularity of the bands during the simulator trials. The band spacing for the 40-deg orientation changed from 300 ft to 700 ft then back to 300 ft in 50-ft steps. It changed from 600 ft to 1,400 ft and back in 100-ft steps for the 75-deg orientation. For the 155-deg orientation, it changed from 1,200 ft to 1,800 ft and back in 200-ft steps. The bands were 300-ft wide, and the center strip was 100-ft wide. Figure 7 provides an

Figure 3. Terrain Texture 2 (overhead view).

Figure 4. Terrain Texture 2 (subject's view).

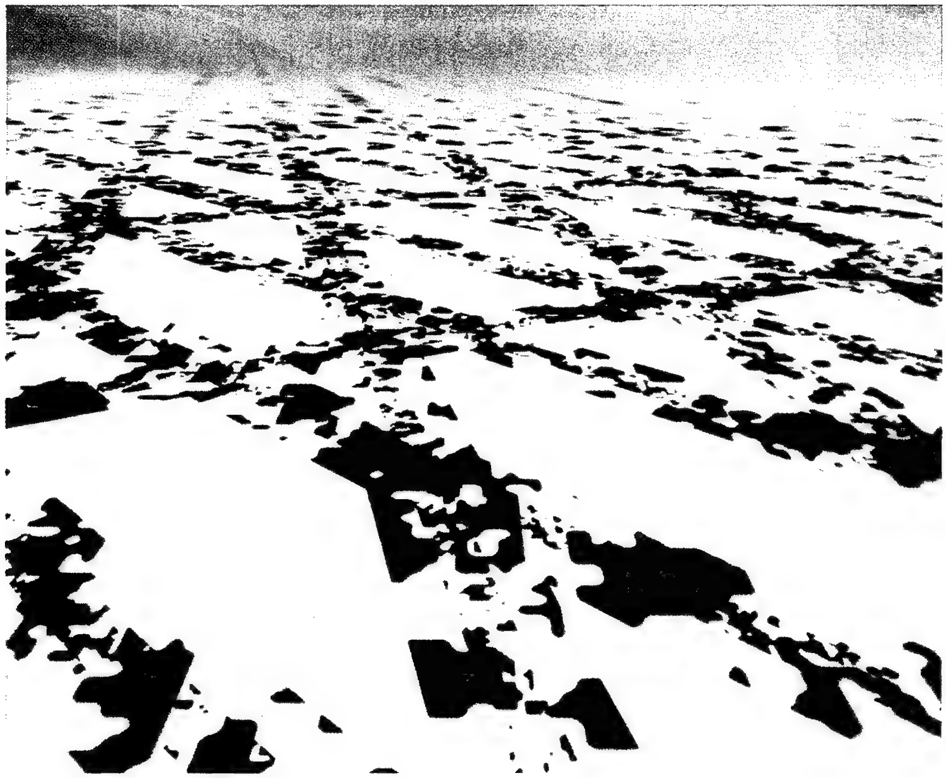

Figure 5. Terrain Texture 3 (overhead view).

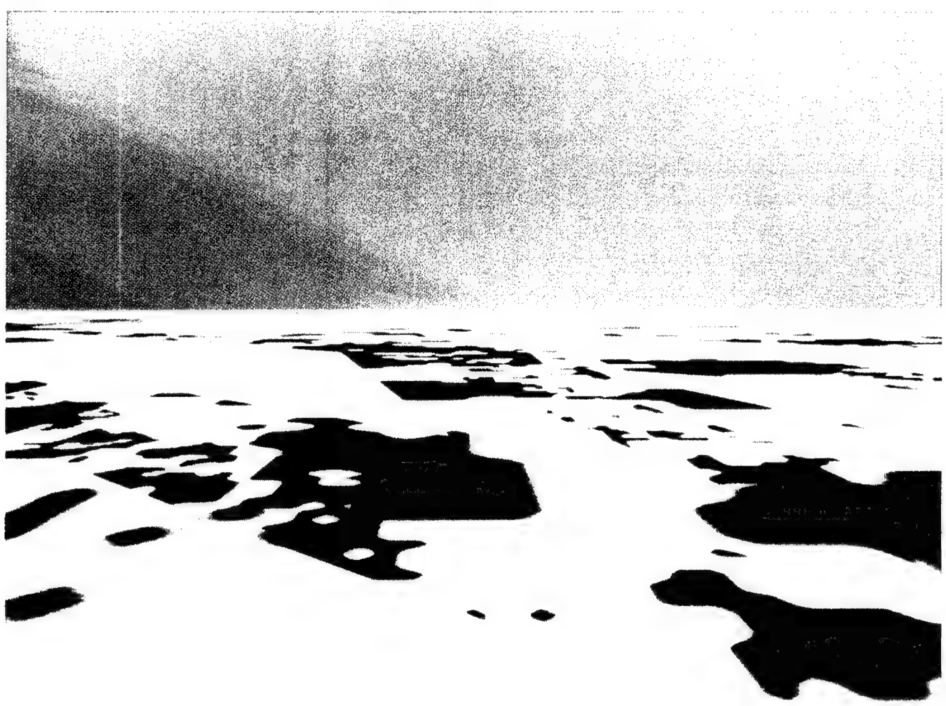

Figure 6. Terrain Texture 3 (subject's view).

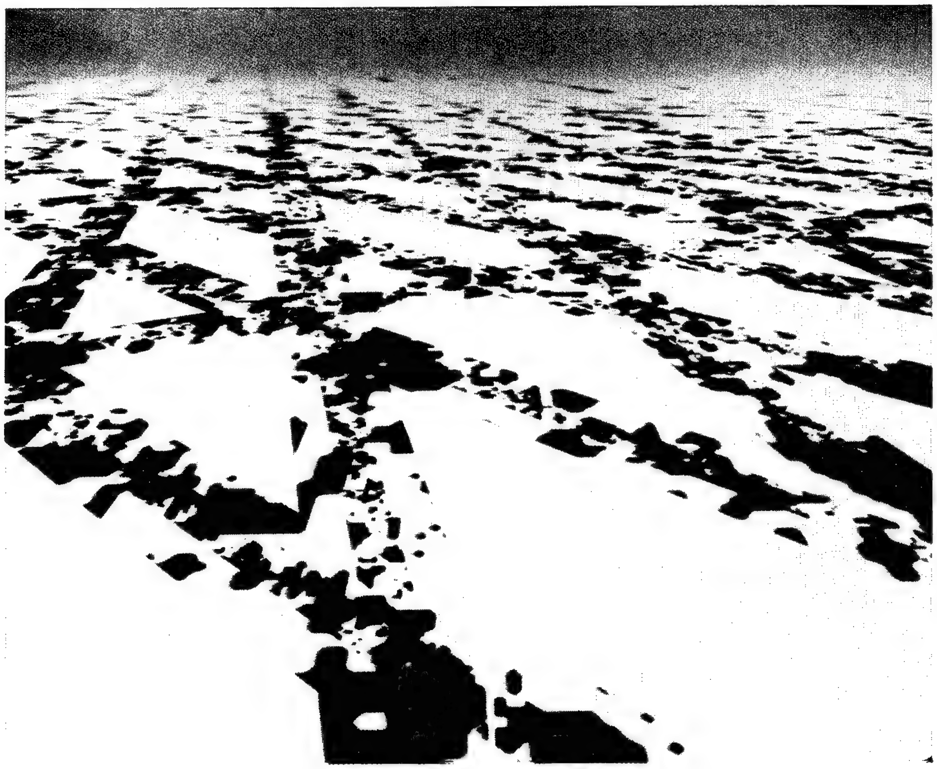

Figure 7. Terrain Texture 4 (overhead view).

Figure 8. Terrain Texture 4 (subject's view).

overhead view of the texture, while Figure 8 shows the subject's view.

The fine detail within the bands was removed and the bands were completely blackened for Terrain Texture 5. The purpose for using this texture condition was to determine if the absence of fine detail reduces the altitude cuing effectiveness of the bands. An overhead view of the texture is presented in Figure 9, the subject's view in Figure 10. The width and spacing of the bands are the same as in Terrain Texture 4.

A separate terrain texture was presented for subject practice. It was the same mathematically produced noise texture that was used to create the detail for the bands in Terrain Textures 2 through 4. An overhead view and the subject's views of the practice texture are shown in Figures 11 and 12.

The luminance level of the sky in the scenes was 1.62 fL. For all terrain textures, the corresponding luminance levels of the brightest tan and darkest black areas were 1.62 fL and 0.25 fL. The contrast between the tan and black luminances in the textures was 84.6%, as computed by the following formula:

$$\text{Contrast (\%)} = \frac{\text{Luminance (max.)} - \text{Luminance (min.)}}{\text{Luminance (max.)}} \times 100$$

Performance Measurement

Ascent and descent discriminability were measured in relation to each of the terrain textures. The measurement procedure was a generalization of the randomized double staircase psychophysical method presented by Cornsweet (1962). This procedure is described below.

Figure 9. Terrain Texture 5 (overhead view).

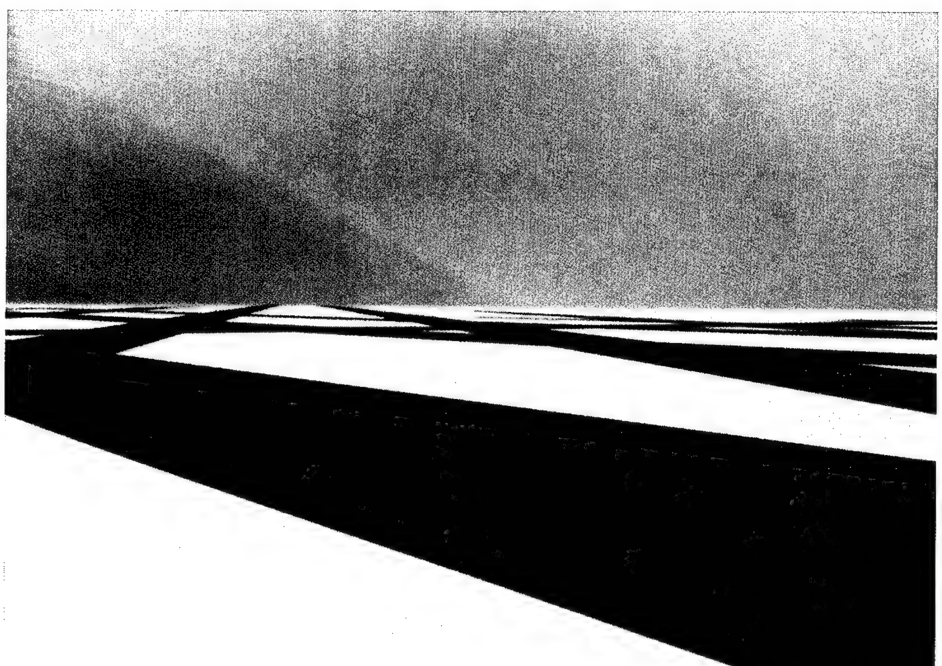

Figure 10. Terrain Texture 5 (subject's view).

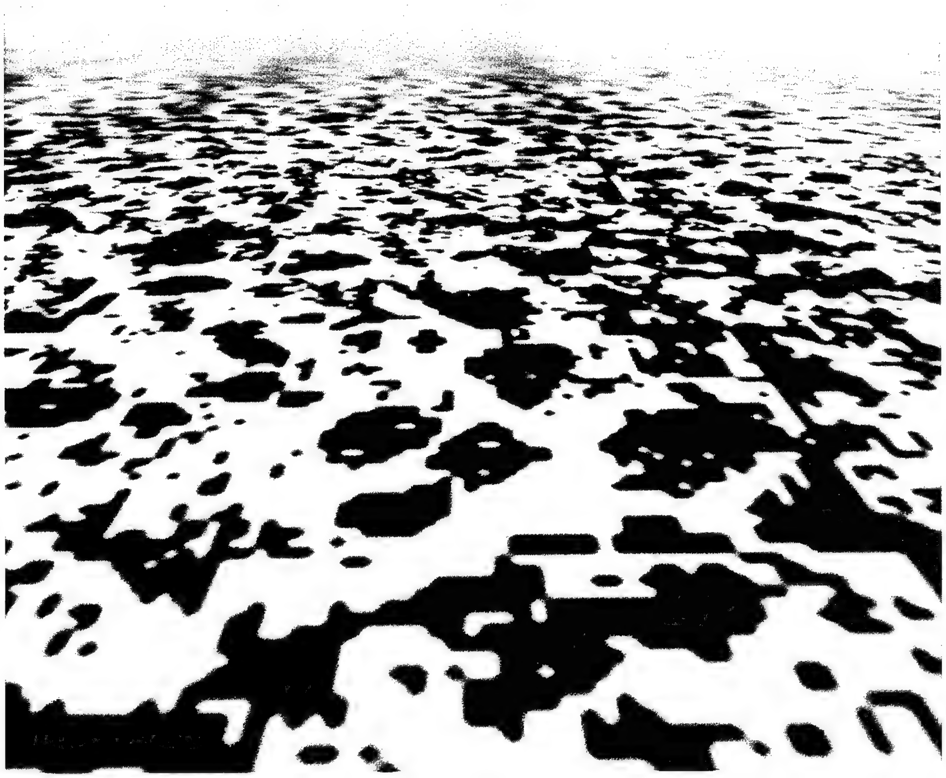

Figure 11. Practice Terrain Texture (overhead view).

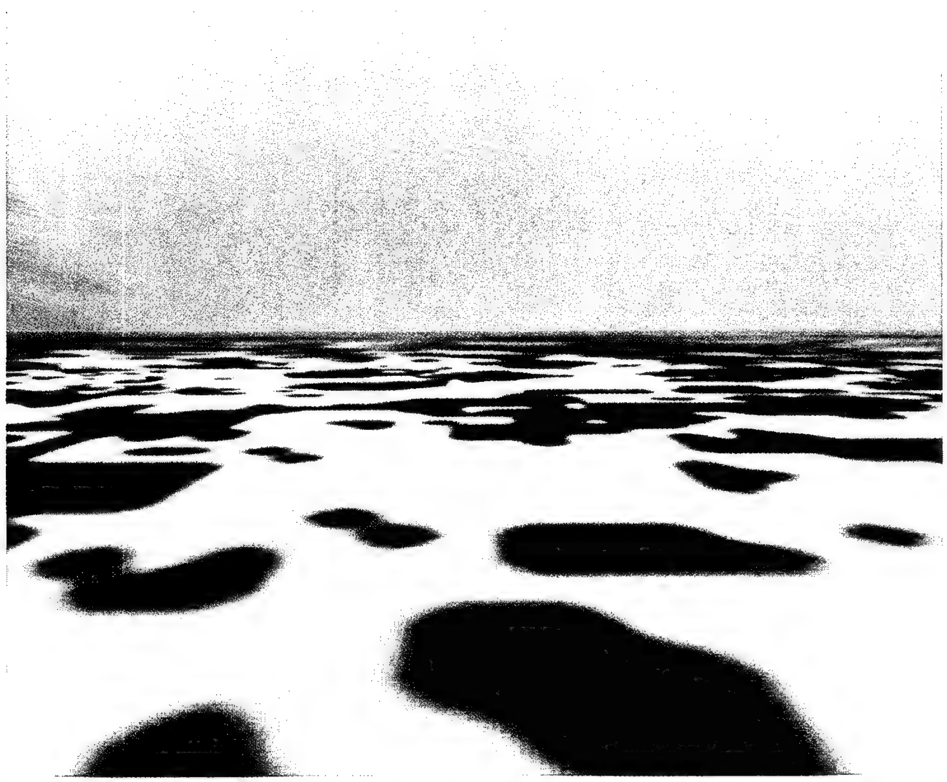

Figure 12. Practice Terrain Texture (subject's view).

In each experimental session, a series of paired simulator trials was presented and one of the terrain texture conditions was used across all trials in the session. An altitude of 100-ft AGL was always depicted in one of the trials and the simulated altitude in the other trial was varied. The former was defined as the standard altitude, the latter was the comparison altitude. The subjects' task was to indicate whether the two altitudes presented in a trial pair appeared to be the same or different by pressing the appropriate switch on the response box.

Simulated airspeed was 500 kt for all trials, and the visual scene portrayed straight-and-level flight. The initial starting position relative to the terrain was varied across the standard and comparison trials so that the second trial in a pair did not start where the first trial ended. Direction of travel was always 90 deg from north. Each trial lasted 5 s. There was a brief but discernable interval between trials within a trial pair of 16.67 ms and a 3 s interval between trial pairs. A cloud-like mask was displayed on the semicircular dome surface in the interval between trials.

The altitudes portrayed in the comparison trials were staircased, and four staircases were produced in each experimental session. Two of the four staircases were used to measure ascent discriminability and the other two were used to measure descent discriminability. These staircases were designated Upper Staircase A and B and Lower Staircase A and B, respectively. Each of the four staircases was represented in each consecutive block of four trial pairs, and the order they were represented was randomized. Furthermore, the order in which the standard and comparison trials were presented in a trial pair was randomized.

Upper Staircase A was started at an altitude of 160 ft, which was 60 ft above the standard. Upper Staircase B was

started at 100 ft, the same as the standard. When the subjects indicated that the altitudes were the same for a trial pair in which the comparison altitude was for an upper staircase, the altitude was increased one step size in the subsequent comparison trial representing the same staircase. Conversely, when the subjects perceived that standard and comparison altitudes were different, the comparison altitude for the staircase was subsequently decreased one step, but the staircase altitude was not allowed to drop below the standard altitude.

The starting altitude of Lower Staircase A was 55 ft, which was 45 ft below the standard. Lower Staircase B began at the same altitude as the standard. When the subjects indicated that the altitudes were the same for a trial pair in which the comparison altitude was for a lower staircase, the altitude in the following comparison trial for the same staircase was decreased one step size. In contrast, the altitude was increased one step for the same staircase in the subsequent comparison when the subject indicated that the standard and comparison altitude were different, except that the comparison altitude could not exceed the standard altitude.

For each staircase, two different step sizes were used. Initially, the step size was 15 ft, then after three response reversals, the step size was changed to 5 ft. A response reversal occurred when a subject pressed a switch (e.g., DIFFERENT) that was dissimilar from the previous switch press (e.g., SAME). The initial larger step size was used to rapidly locate the region where the subject could detect a difference in altitude, and the three reversals were employed to stabilize the staircases in those regions before the finer, 5-ft step sizes were introduced. The starting points for both upper and lower staircases and the initial and final staircase step sizes were determined in a series of preliminary tests.

Actual test data are shown in Figure 13 for one of the subjects to illustrate the four staircases. The solid line across the center of the figure represents the standard altitude, and the circles and squares are indicative of the altitudes associated with the sequential comparison trials. For any given staircase trial number in the figure, all four staircase altitudes were presented before moving to the next set of four staircase altitudes.

There were a minimum of 20 paired trials following the three response reversals in a staircase. Because the number of trials required to attain the three reversals within a staircase varied, the 20 trials were attained for some of the staircases before others. In these instances, extra trials were added to the completed staircases so that the four staircases would continue to be represented in the consecutive blocks of four trial pairs. The extra trials were dropped in the data analysis.

A practice session was also provided and the same performance measurement methodology was used with the following exceptions. Upper Staircase A was started at a simulated altitude of 175 ft and Lower Staircase A began at 25 ft. Staircase step size was changed after one reversal and there were five trials for each of the staircases following the reversal. The practice ground texture was used exclusively for practice.

Experimental Design

The experimental design encompassed three independent variables: terrain texture condition, direction of altitude change, and type of subject. There were five levels of texture (Terrain Textures 1 through 5), two directions of altitude change (ascent and descent), and two types of subjects (pilots and nonpilots). Texture condition and direction of altitude change

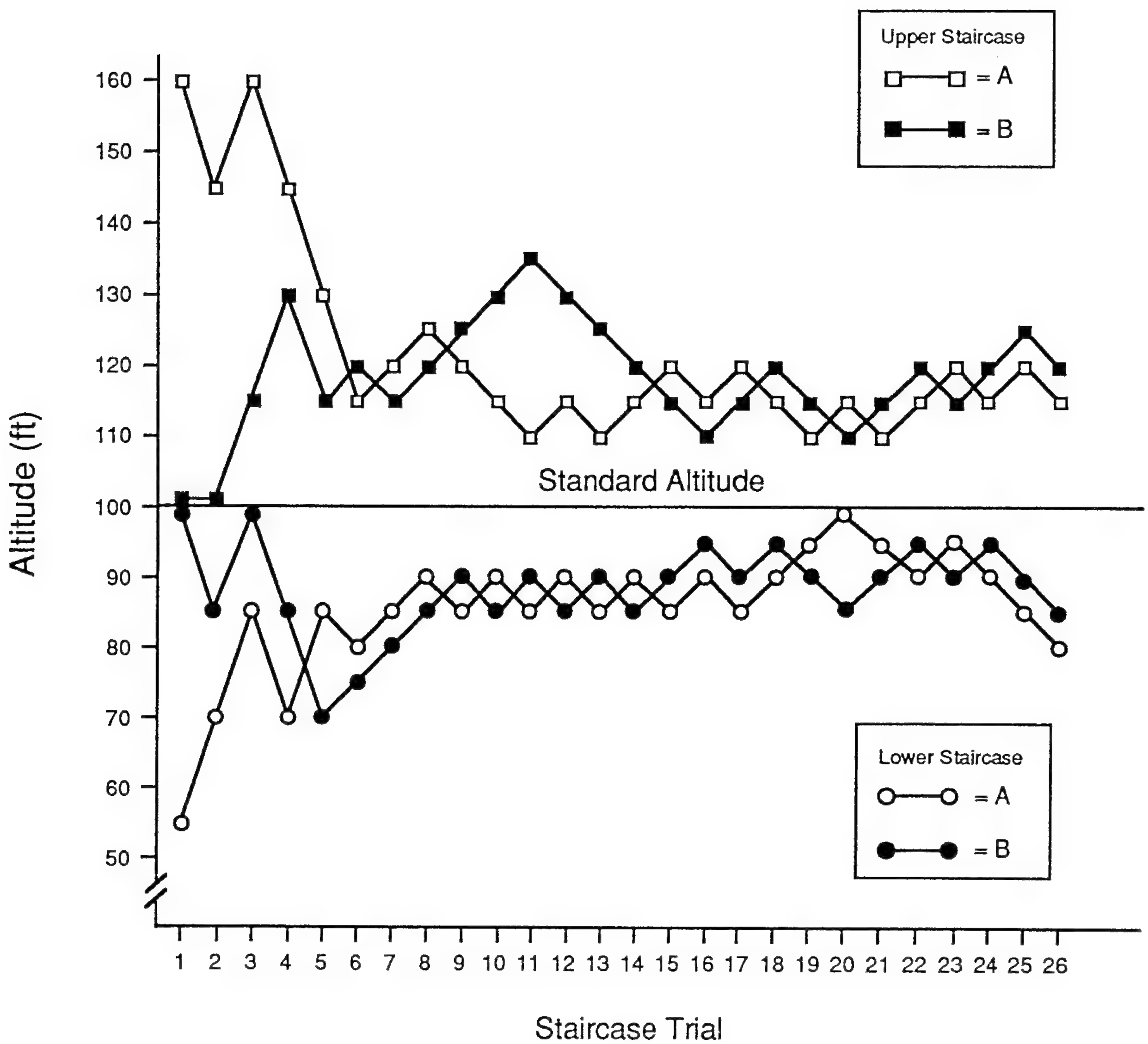

Figure 13. Illustration of the staircase measurement methodology.

were within-subjects factors and type of subject was a between-subjects factor.

Procedure

Each subject participated in five test sessions, and a separate terrain texture was presented in each session. The order in which the textures were presented over the five sessions was randomized for each subject. The practice exercise was presented once, just prior to the subject's first test session. Standardized instructions, which described the goals of the research and the subject's task, were given to the subjects preceding the practice. The task requirements were briefly reviewed before each subsequent test session.

Results

The difference between the standard and comparison altitudes within a trial pair constituted the dependent measure. A logarithmic transformation was applied to each difference after a value of one was added to eliminate zero differences. For the analysis, the transformed differences were averaged over the 20 trials following the third reversal in a staircase. In addition, the means associated with the two upper staircases for each of the texture conditions were averaged and the means corresponding to the two lower staircases were averaged.

The logarithmic transformation was applied because the frequency distribution of the differences was skewed. That is, the frequencies were concentrated near the standard altitude and they tapered off as the distance from the standard increased.

The data were subjected to a split-plot analysis of variance (ANOVA) with type of subject forming the whole plot (between-subjects) factor and texture condition and direction of altitude change forming the split-plot (within-subjects) factors. The main effect for texture condition was statistically significant, $F(4,72) = 2.74$, $p < 0.05$. To facilitate comparison of the group differences, the mean altitudes were transformed from the logarithmic scale to the equivalent scale in feet. The mean $\log_2$ altitude differences associated with the five textures for the main effect of texture condition are provided in Table 1 along with their equivalent altitudes. Figure 14 depicts the means for both groups of subjects across the five textures in conjunction with both the ascent and descent detections.

Table 1. Mean Altitude Difference between the Standard and Comparison Trials for the Texture Condition Main Effect

Texture Condition	Log_2 Altitude Difference (ft)	Equivalent Altitude Difference (ft)
1	3.59	11.06
2	3.66	11.61
3	3.87	13.79
4	3.39	9.47
5	3.92	14.09

A series of planned comparisons was subsequently conducted to assess the relative effects of the features comprising the textures. Table 2 identifies the specific texture conditions that were compared, the corresponding features of the textures that were compared, and the probability (p) value associated with

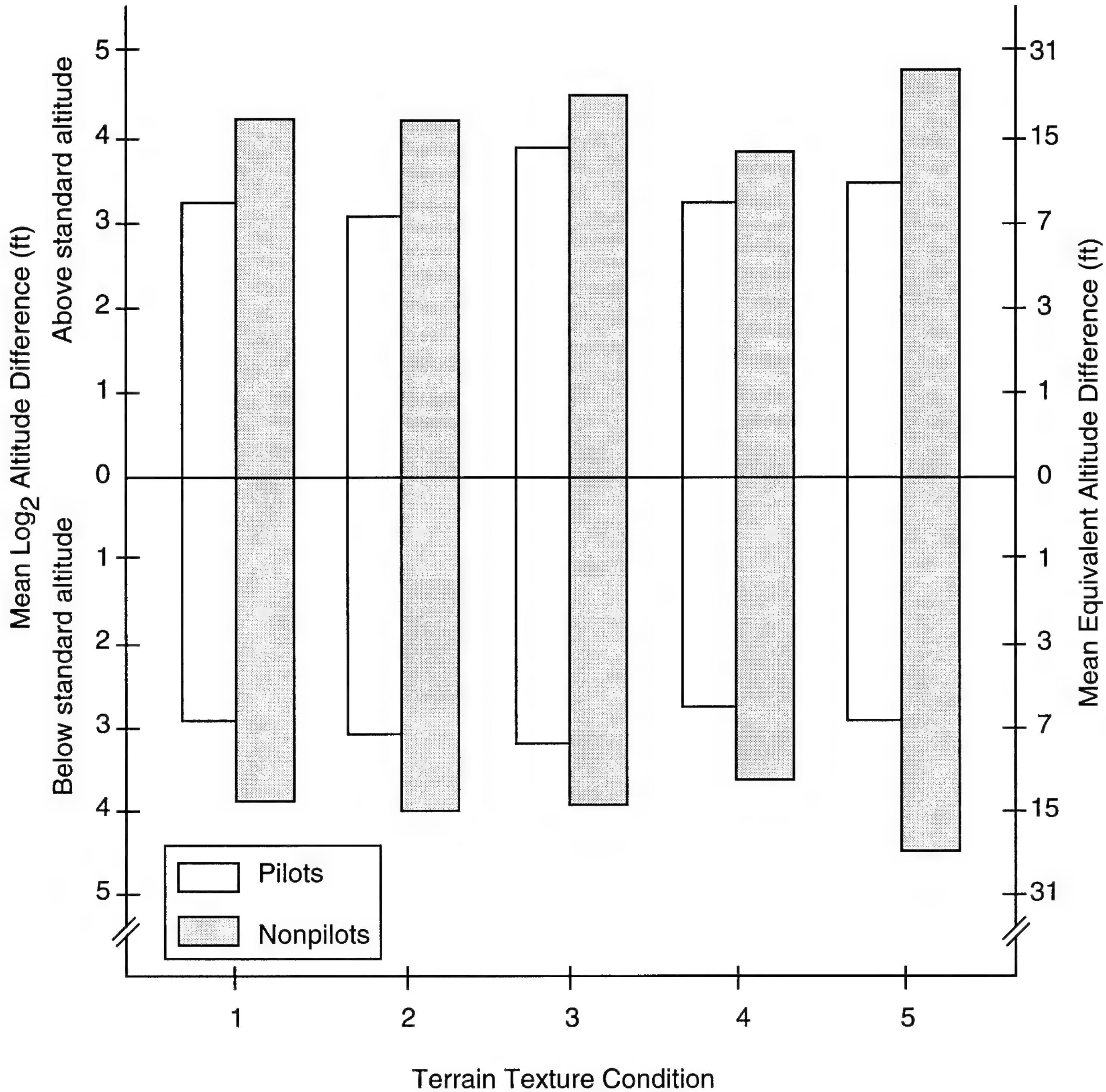

Figure 14. Mean altitude difference as a function of terrain texture condition, direction of altitude change, and type of subject.

Table 2. Planned Comparisons for the Texture Condition Main Effect

Textures Compared	Texture Features Compared	p
1 v 2, 3, 4, & 5	No bands v band structure	0.42
2 v 3, 4, & 5	100-ft v 300-ft bands	0.63
2 v 3 & 4	100-ft v 300-ft bands (excluding 300-ft, solid black bands)	0.91
2 & 3 v 4 & 5	Regularly v irregularly spaced bands	0.37
3 v 4 & 5	Regularly v irregularly spaced bands (300-ft bands only)	0.15
4 v 2 & 3	Irregularly v regularly spaced bands (textured bands only)	0.02
5 v 2, 3, & 4	Solid black v textured bands	0.08
5 v 3 & 4	Solid black v texture bands (300-ft bands only)	0.09
2 v 3	100-ft v 300-ft bands (regularly spaced bands only)	0.22
3 v 4	Regularly v irregularly spaced bands (300-ft, textured bands only)	0.009
4 v 5	Textured v solid black bands (irregularly spaced bands only)	0.006

each comparison. As can be seen in the table, the data for the texture conditions that shared the same features within a given comparison were combined. Three of the planned comparisons achieved statistical significance ($p < 0.05$). These comparisons indicate that: (a) performance was better with the irregularly spaced textured bands than with the regularly spaced textured bands, (b) it was better with the irregularly spaced textured bands than with the irregularly spaced solid black bands, and (c) it was better with the 300-ft textured bands that were

irregularly spaced than with the 300-ft textured bands that were regularly spaced. In other words, the only texture condition that appeared to have a different effect on performance from the other conditions was Terrain Texture 4 with the irregularly spaced, 300-ft-wide textured bands. Subject performance under Terrain Texture 4 was superior to performance under any of the other texture conditions. Performance under the other four conditions was essentially the same.

None of the interactions involving the texture condition factor were significant. The absence of a significant interaction between texture condition and direction of altitude change indicates that the relative effects of the texture conditions were comparable for both ascent and descent discrimination. Further, the lack of a significant texture condition by type of subject interaction signifies that the relative effects of the textures were similar for both the pilots and nonpilots.

A significant main effect for direction of altitude change was also obtained in the ANOVA, $F(1,18) = 29.47$, $p < 0.01$. Table 3 provides the mean $\log_2$ and equivalent altitude differences in feet for both directions of altitude change. Comparison of the data reveals that the subjects were more efficient distinguishing a descent than an ascent. There were no significant interactions with the direction of altitude change, indicating that difference between ascent and descent discriminability was approximately the same across the various texture conditions for both pilots and nonpilots.

We also observed in the analysis that the main effect for type of subject was significant, $F(1,18) = 11.16$, $p < 0.01$. The altitude differences for both the pilots and nonpilots are shown in Table 4. It is evident that the pilots were more sensitive to

Table 3. Mean Altitude Difference between the Standard and Comparison Trials for the Direction of Altitude Change Main Effect

Direction of Altitude Change	Log_2 Altitude Difference (ft)	Equivalent Altitude Difference (ft)
Ascent	3.88	13.67
Descent	3.50	10.32

Table 4. Mean Altitude Difference between the Standard and Comparison Trials for the Type of Subject Main Effect

Type of Subject	Log_2 Altitude Difference (ft)	Equivalent Altitude Difference (ft)
Pilots	3.21	8.27
Nonpilots	4.16	16.92

the differences between the standard and comparison altitudes than the nonpilots. None of the interactions involving type of subject was significant, which implies that altitude discriminability did not vary as a function of texture or direction of altitude change between the two types of subjects.

Discussion

The analysis indicated that, except for Terrain Texture 4, the altitude cuing effectiveness of the various texture conditions was very similar. Inspection of Figure 14 clearly shows, however, that the differences in performance between Terrain Texture 4 and the other conditions were relatively minor.

In the case of descent detection, the difference in performance between the best and worst texture conditions was only 2.60 ft for the pilots and 10.95 ft for the nonpilots. For ascent detection, the respective differences were only 6.05 ft and 12.32 ft. This suggests that in an applied setting, these textures would provide similar altitude cuing.

The planned comparisons for the significant main effect of texture condition (Table 2) showed the texture characteristics that influenced altitude cuing effectiveness and the characteristics that were irrelevant. First, when the texture condition without the band structure was compared with the combination of textures that contained the bands, no difference in performance was observed. This signifies that the presence of bands in the terrain texture was neither conducive nor disruptive to the detection of change in aircraft altitude.

Next, we compared the effects of various characteristics of the bands in the texture conditions. Comparisons that were made between the texture comprised of the 100-ft-wide bands and the textures containing the 300-ft-wide bands yielded no significant differences, which means that increasing the amount of detail on the terrain through the use of the wider bands had no effect on performance. We also found no difference in performance when the combination of textures with the regularly spaced bands was contrasted with the combination of the textures consisting of the irregularly spaced bands. Nor did we find a significant difference when the texture condition containing regularly spaced, 300-ft-wide bands was compared with the combination of the two textures that contained the irregularly spaced, 300-ft-wide bands.

When we repeated the latter two comparisons after removing the performance data associated with the texture condition containing the irregularly spaced solid black bands, significant

differences in performance between the texture conditions were observed. In both comparisons, performance was significantly better with the texture comprised of the irregularly spaced bands than the regularly spaced bands. Based on these findings, we recommend that if a terrain texture is used in simulator training that is structured with distinct borders, the borders should be irregularly spaced.

Lastly, we compared the effects of the texture comprised of the irregularly spaced solid blank bands with the textures made up of the bands containing the fine detail. Only one of the comparisons was statistically significant. This was the comparison between the black-banded texture and the texture containing the irregularly spaced bands with the fine detail. Performance was better for the latter texture condition, indicating that the absence of detail had a debilitating effect on the altitude cuing effectiveness of the irregularly spaced bands. This effect was evident, though, only in relation to the nonpilots, as Figure 14 shows. The pilots on the average performed almost the same with these two texture conditions.

The main effect for direction of altitude change revealed that simulated descent was significantly more discriminable than ascent. The reason for this stems from the fact that the apparent changes in the spatial and temporal characteristics of the texture, which signify a change in altitude, increase at a greater rate the closer the observer is to the terrain surface. These changes include an apparent increase in the size of the texture detail, an apparent increase in the spacing of the detail, and an apparent increase in the speed of the detail streaming under the simulated aircraft. Because the rates increase as the observer nears the terrain, there was a greater disparity of the spatial and temporal characteristics between the standard and comparison altitudes when the comparison was below the standard (representing a descent) than when the comparison

was an equal distance above the standard (representing an ascent), which made the detection of descent easier. In order to equate the disparity between the standard and comparison trials in the ascent detections with the disparity in the descent detections, the altitude of the comparison altitude in the ascent trials had to be increased.

These findings are consistent with other investigations in which the effects of simulated ascending and descending conditions on performance have been compared. Kleiss (1992) compared ascent and descent detection performance and manipulated four visual scene factors (altitude change rate, object density, object type, and the presence versus absence of texture). With respect to the direction of altitude change, he found that subjects could detect descent more quickly and more accurately than ascent. Owen and Wolpert (1987) applied ascent and descent forcing functions (wind shears) in an active altitude control task and also varied texture flow rate, edge rate, fractional (percent) loss in altitude, and preview period. In the main, they reported that performance was better for descent than ascent.

The analysis also indicated that the pilots could discriminate differences in altitude between the standard and comparison trials significantly better than the nonpilots. This suggests that the flight experience of the pilots facilitated the use of the various ground texture cues that specify a change in altitude. Reardon (1988) also found that pilots were more sensitive to texture cues than nonpilots. She used a landing judgment task in which simulated landing approaches were viewed on a color monitor. The simulation halted in "midair" on the approaches, and the observer's task was to indicate where they would land if they continued on the same flight path. Four different runway scenes were presented in which the amount of runway texture was varied. It was reported that observer

performance was influenced by runway texture, approach angle, simulated sink rate, and offset angle, as well as by the type of observer. For this task, the pilots estimated the touchdown point significantly more accurately than the nonpilots.

EXPERIMENT 2

The second experiment constituted a partial replication of Experiment 1. In Experiment 2, the altitude cuing effectiveness of four of the five textures previously used were compared in relation to the direction of altitude change. In addition, we varied texture luminance contrast in order to simulate normal daylight and low-contrast, dawn/dusk terrain illumination. The same ascent and descent discrimination methodology used in the first experiment was employed in Experiment 2. All of the observers were pilots.

Method

Subjects

The subject sample consisted of 24 male U.S. Air Force T-38 and T-37 instructor pilots from Williams Air Force Base, AZ, and Air National Guard F-16 pilots temporarily assigned to the 162d Tactical Fighter Group at Tucson, AZ. The mean, minimum, and maximum accumulated military flight time of the pilots were approximately 1,025, 290, and 3,000 hr, respectively. Visual contrast sensitivity was measured for each subject using the same procedure described in the first experiment. The measurements indicated that the subjects had normal contrast sensitivity functions. Additionally, the visual acuity of each subject was normal or corrected to normal.

Apparatus

The same apparatus used in the first experiment was employed in Experiment 2.

Terrain Textures

Four of the five terrain textures that were compared in the previous experiment were used in the present investigation along with the practice texture. Terrain Texture 2 was not used.

Luminance Contrast

Each of the four textures was crossed with two levels of luminance contrast: 41.9% and 84.6%. The luminances of the brighter tan and darker black surfaces associated with the two contrast levels are provided in Table 5. The sky luminance within each contrast condition was the same as the luminance of the tan surfaces.

Table 5. Luminance Levels of the Texture Surfaces for the Low and High Contrast Conditions

Luminance Contrast	Tan Surfaces (fL)	Black Surfaces (fL)	Contrast (%)
Low	0.43	0.25	41.9
High	1.62	0.25	84.6

Performance Measurement

Ascent and descent discrimination performance was measured using the same staircase methodology previously described. The altitude differences between the standard and comparison trials in the trial pairs were transformed and averaged for the analysis in the same manner as the first experiment.

Experimental Design

The independent variables were: terrain texture condition, direction of altitude change, and luminance contrast. There were four texture conditions, two directions of altitude change, and two luminance contrast conditions. Texture condition and direction of altitude change were within-subjects factors and luminance contrast was a between-subjects factor. Because this experiment included a partial replication of the first experiment, the repeatability of the results obtained in Experiment 1 was considered as important as the assessment of the effects of reduced luminance contrast. Therefore, we chose to use texture condition as the within-subjects factor. The limited availability of pilots for testing purposes required the use of a balanced, incomplete block research design in the present investigation. With this design, each of the pilot subjects was tested with only two of the four terrain textures.

Procedure

The subjects were randomly assigned to two separate groups, each consisting of twelve subjects. One group was administered low-contrast textures and the other was administered high-contrast textures. Each of the subjects was presented two different textures. Within each group, the texture presentations

were counterbalanced such that each of the textures was presented an equal number of times and each texture combination taken two at a time was represented. Two test sessions were required for each subject and one of the textures was presented in each of the sessions. The practice exercise, using the same practice measurement methodology and practice texture condition as in the first experiment, was presented once, immediately preceding the first test session. The luminance contrast of the practice texture was the same as the contrast of the two experimental texture conditions the subjects were presented. Standardized instructions were given at the start of practice and the task requirements were reviewed before each test session.

Results

The performance data were subjected to a three-factor split-plot ANOVA. The analysis indicated that the main effect for texture condition was not significant ($p > 0.05$). The means of the four texture conditions are presented in Table 6. None of the interactions involving texture condition were statistically significant.

The main effect for direction of altitude change was significant, $F(1,22) = 38.39$, $p < 0.01$. The mean $\log_2$ and equivalent altitude differences for both directions of altitude change are provided in Table 7. As in the first experiment, the subjects could more efficiently discriminate a simulated descent than an ascent. None of the two-way interactions involving the direction of altitude change or the three-way interaction were statistically significant, suggesting that the descending discriminations were easier over the range of ground texture and luminance contrast conditions we compared.

Table 6. Mean Altitude Difference between the Standard and Comparison Trials for the Texture Condition Main Effect

Texture Condition	Log_2 Altitude Difference (ft)	Equivalent Altitude Difference (ft)
1	3.89	13.82
3	3.72	12.22
4	3.51	10.41
5	3.69	11.94

Table 7. Mean Altitude Difference between the Standard and Comparison Trials for the Direction of Altitude Change Main Effect

Direction of Altitude Change	Log_2 Altitude Difference (ft)	Equivalent Altitude Difference (ft)
Ascent	3.99	14.88
Descent	3.42	9.71

The analysis revealed that the main effect for luminance contrast and the interactions involving luminance contrast failed to achieve significance. Table 8 presents the mean altitude differences for the two contrast conditions. This finding indicates that the simulated dawn or dusk lighting did not substantially impair ascent or descent detection.

Table 8. Mean Altitude Difference between the Standard and Comparison Trials for the Luminance Contrast Main Effect

Luminance Contrast	Log_2 Altitude Difference (ft)	Equivalent Altitude Difference (ft)
Low (41.9%)	3.96	14.52
High (84.6%)	3.45	9.96

Discussion

The significant effects of the texture conditions observed in the first experiment were not replicated in Experiment 2. There are two reasons for the absence of a significant texture effect in this experiment. First, the incomplete block design used in Experiment 2 is not as powerful as the complete block design in the first experiment. Thus, the difference may have been due to a lack of statistical power. Second, we observed in Experiment 1 that the texture effect was due to Terrain Texture 4 producing superior performance relative to the other conditions. It may be noted in Table 6 that Terrain Texture 4 is again associated with superior performance compared to the other texture conditions. However, this difference is not as great as that obtained in Experiment 1.

As in the first experiment, we observed in Experiment 2 that subjects could discern simulated descents significantly better than ascents. Also, comparison of Tables 3 and 7 shows that the average amount of altitude change required to detect a difference between the standard and comparison altitudes was highly similar in both experiments. When aircraft ascent was simulated, the mean altitude difference was 13.67 ft in Experiment 1 and 14.88

ft in Experiment 2. For the trials portraying aircraft descent, the differences were respectively 10.32 ft and 9.71 ft.

The low contrast texture conditions were created in our second experiment by lowering the luminance of the brighter tan surfaces in the textures. An alternative method to reduce texture contrast would have been to brighten the black surfaces. We chose the former approach in order to simulate dawn or dusk viewing conditions. Under this type of lighting, we found that the detection of altitude change was not adversely affected.

These findings are consistent with an earlier helicopter investigation in which the effects of reduced illumination were examined. Armstrong, Hofmann, Sanders, Stone, and Bowen (1975) exposed helicopter pilots to four different visual conditions: (a) unaided eye under normal daylight illumination, (b) unaided eye under simulated night illumination, (c) aided eye with 40-deg field-of-view (FOV) night vision goggles under simulated night illumination, and (d) aided eye with 60-deg FOV night vision goggles under simulated night illumination. The night illumination was simulated through the use of goggles with neutral density filters. The resultant illumination was equivalent to approximately 25% of full moon illumination (i.e., 25% moon illumination = 0.008 fL). The investigation was conducted using an actual helicopter and both the speed and altitude of the aircraft were varied. Flights were made over forested terrain interlaced with farm land. The subjects, who were helicopter pilots, served only as observers; they did not have control of the aircraft. In one task, the subjects were asked to judge their altitude above the terrain. It was found that neither mean signed altitude error (average constant error) nor mean unsigned altitude error (average absolute error) significantly varied across the four visual conditions.

In a somewhat similar study, Fineberg and Dressel (1977) observed that distance judgements in simulated helicopter flights were not influenced by reduced illumination. They presented scenes on a video monitor made from a helicopter flying at nap-of-the-earth (NOE) altitude over a forest. Subjects, who had no previous NOE flight experience, made distance judgements to an obstacle (tree) in the flight path. One of the variables manipulated in this investigation was the level of scene illumination. The illumination from the monitor was filtered to provide light levels of 0.01, 0.001, and 0.0001 fL, which resembled full moon, partial moon, and starlight-only illumination. The subject's task was to indicate the minimum breakaway distance from the obstacle at various closing velocities. Analysis of mean distance errors from the analytically determined breakaway point revealed that the changes in scene illumination did not produce a corresponding change in distance judgement performance.

CONCLUSIONS AND RECOMMENDATIONS

The terrain textures compared in the present research provided similar altitude cuing. The terrain textures structured with bands that provided distinct borders neither facilitated nor impaired the detection of altitude change relative to the texture condition that was devoid of bands. Furthermore, variations in the size of the bands, the regularity of the spacing between bands, and the detail within the bands had little or no effect on altitude change detectability. Because the altitude cuing effectiveness of the terrain textures was virtually the same, we recommend the use of the texture condition that is most consistent with the specific real-world environment in which the low-altitude, high-speed flight tasks will be performed.

Simulated descents were easier for the subjects to recognize than ascents due to the apparent increase in the rate of change of the spatial and temporal characteristics of the texture details the closer the simulated aircraft was to the terrain surface. In order to sensitize pilots to changes in altitude, we recommend that pilots be trained to interpret the various changes that appear to occur as a function of aircraft ascent and descent. In the case of descent, these changes include an apparent increase in the size of the texture detail, an apparent increase in the spacing of the detail, and an apparent increase in the velocity of the detail flowing under the aircraft.

No difference in the detection of altitude change was observed between the low- and high-contrast texture conditions. This finding indicates that dawn or dusk terrain illumination can be simulated without adversely affecting the altitude cuing effectiveness of the terrain textures.

The pilot subjects in the present research were significantly more sensitive to changes in simulated aircraft altitude than the nonpilot subjects. Therefore, we recommend the use of pilots in future endeavors aimed at the assessment of the altitude cuing effectiveness of terrain texture.

It should be borne in mind that the subjects served as observers only and could focus their attention on the terrain textures presented in the simulator trials. Under typical low-altitude, high-speed training conditions requiring control of the aircraft and visual search for ground targets, navigation checkpoints, and air defense batteries, pilots would not be able to pay as close attention to the textures. It is anticipated that under these conditions, altitude deviations would be much larger than the deviations observed in this research.

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